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INCREASED EPHEMERIS ACCURACY USING ATTITUDE-DEPENDENT AERODYNAMIC FORCE COEFFICIENTS FOR INERTIALLY STABILIZED SPACECRAFT

by

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ABSTRACT

Current techniques for generating spacecraft ephemerides typically use a constant value of the ballistic coefficient during orbit propagation. This is due in part to the added complexity of calculating attitude-dependent aerodynamic forces and in part to the great inaccuracy in the prediction of the atmospheric density, which would result in substantial orbital position errors even if the ballistic coefficient were to be determined exactly at all times. Assuming a constant ballistic coefficient, however, introduces errors that may be as large as those caused by the density uncertainty. For inertially-stabilized spacecraft, these errors may be reduced either by calculating orbit-averaged ballistic coefficients for each viewing attitude, or by calculating aerodynamic force coefficients for the appropriate geometry at each integration step.

This report describes briefly the FREEMAC program used to generate the aerodynamic coefficients, as well as associated routines that allow the results to be used in other software. These capabilities are applied in two numerical examples to the short-term orbit prediction of the GRO and HST spacecraft. Predictions using attitude-dependent aerodynamic coefficients were made on a modified version of the PC-based Ephemeris Generation Program (EPHGEN) and were compared to definitive orbit solutions obtained from actual tracking data. The numerical results show improvement in the predicted semi-major axis and along-track positions that would seem to be worth the added computational effort.

Finally, other orbit and attitude analysis applications are noted that could profit from using FREEMAC-calculated aerodynamic coefficients, including orbital lifetime studies, orbit determination methods, attitude dynamics simulators, and spacecraft control system component sizing.

1.0 INTRODUCTION

In the course of planning and supporting a low-Earth-orbit satellite mission, both long- and short-term orbit predictions are required. Long-term predictions (over months or years) are used to plan orbit reboost maneuvers and to estimate time of atmospheric reentry, while short-term predictions (over days or weeks) are used to schedule tracking resources and scientific data collection. Since the position of a satellite in low Earth orbit is highly dependent on aerodynamic drag, this effect must be modeled as well as possible for accurate orbit predictions.

Aerodynamic drag is given by:

$$\mathbf{D} = \tfrac{1}{2}\rho \; |\mathbf{v}_r| \; C_d A \; \mathbf{v}_r$$

where

ρ = atmospheric density
$\mathbf{v}_r$ = relative velocity of spacecraft and atmosphere
C_d = coefficient of drag
A = satellite cross-sectional area

The predominant error source in the drag calculation is due to density modeling inaccuracies. Substantial errors may also be introduced through the C_d and A terms, however; these terms vary with attitude and orbit position, and can be difficult to calculate. The benefits of calculating attitude-dependent C_dA values have generally been considered in the past to be not worth the computational effort required, especially given large errors due to density modeling which would still cause errors in the drag estimate even if values for C_dA were to be calculated perfectly at each instant. The C_dA term in the drag equation is therefore typically held constant over the period of prediction, often for the spacecraft's entire operational lifetime.

As might be imagined, using such a constant C_dA introduces substantial errors in addition to those due to the density uncertainty. These errors may be quite large, especially for spacecraft with large appendages, and may approach in magnitude the errors due to density mismodeling.

This report presents recent work done in Goddard's Flight Dynamics Analysis Branch that enables attitude-dependent drag coefficients and areas to be calculated. In particular, software tools are described that calculate these coefficients and permit them to be accessed easily in a variety of orbit and attitude applications. These routines are applied to the case of short-term orbit determination of inertially stabilized spacecraft through numerical examples using real data from the Hubble Space shielding elements and hit the spacecraft in a region FREEMAC considers in shadow, causing an additional unmodeled force. Thus, the actual C_d may be somewhat greater than the FREEMAC value; this effect will be greater for long, thin spacecraft and for spacecraft with long shielding appendages.

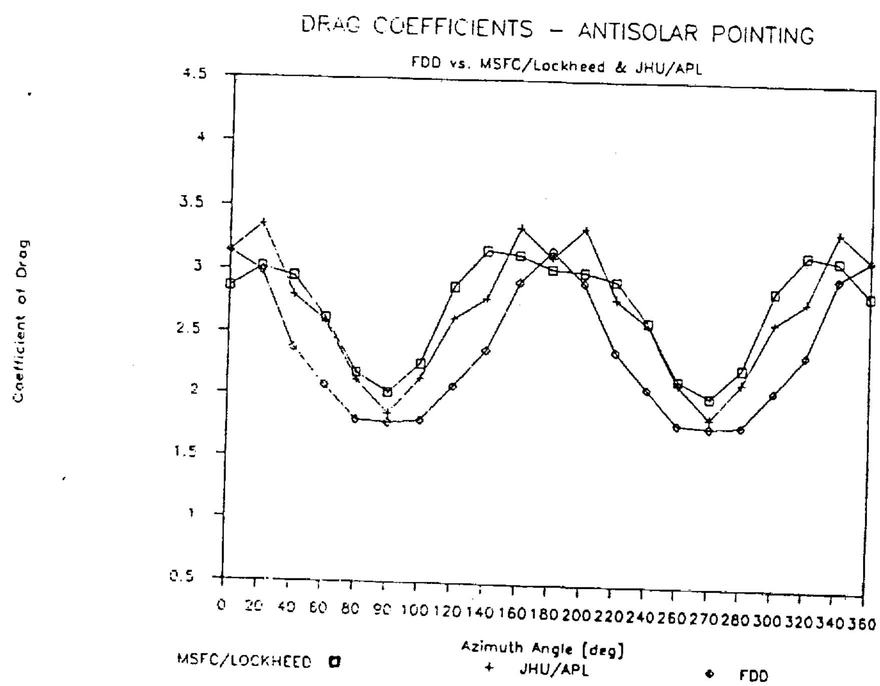

Figure 4.

displayed on with a CAD graphics package. By viewing the model with the CAD package, the user can quickly determine whether the constituent basic shapes are of the right size and are oriented correctly. Figure 2 and 3 show CAD displays of the GRO and HST models used in the numerical examples presented in the report.

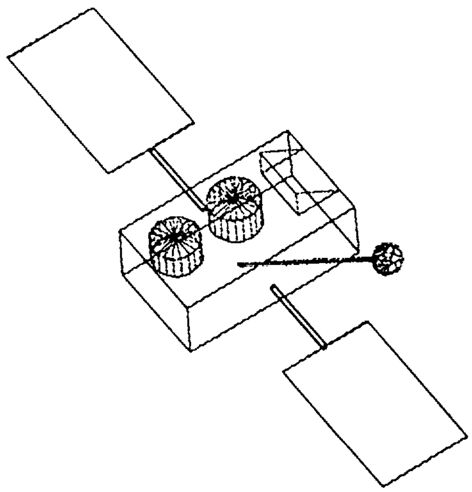

Figure 2.
GRO

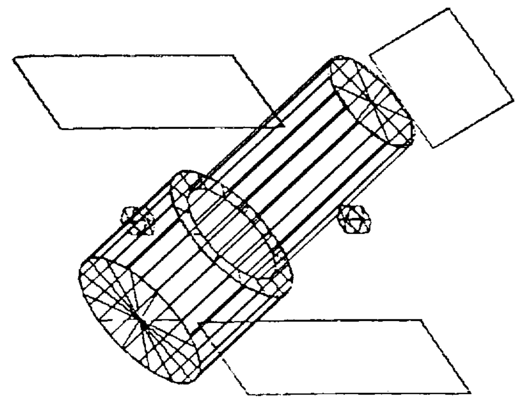

Figure 3.
HST

A.5 VALIDATION OF FREEMAC RESULTS

Another reason for hesitation in using FREEMAC in the past was the concern that the program had not been rigorously tested. Over the past few years, confidence in the program has increased as hand-calculations of such easily-calculable quantities as area has agreed with the program results. Validating the aerodynamic coefficients has been more complicated, however, and has been done only partially by comparing FREEMAC C_ds for HST to those used at Marshall Space Flight Center (MSFC) and at Johns Hopkins' Applied Physics Laboratory (APL). The FREEMAC numbers agree well with the others, as Figure 4 shows for a sample attitude/orbit configuration.

A.6 A CAUTIONARY NOTE REGARDING FREEMAC COEFFICIENTS

It should be noted that FREEMAC cannot account for the drag due to inflow behind shielding elements. This additional drag source is due to the atmospheric particles having an intrinsic velocity due to their thermal motion; this velocity, when added vectorally to the spacecraft's, can particles to flow in behind

A.2 USING FREEMAC OUTPUT

In order to access the results of FREEMAC with other computer programs, a coefficient file was output from FREEMAC, and an interpolation subroutine was written to return the FREEMAC-determined coefficients for any given body frame velocity vector direction input to it. In particular, the eight coefficients listed above were calculated and output to the file for velocity vector directions spaced every 10° in body frame right ascension and declination. The output accessing subroutine obtains the coefficient values for any arbitrary velocity direction using a quadratic interpolation scheme using 16 data points from the FREEMAC coefficient file. This subroutine allows quick access to FREEMAC results, and can be inserted into a wide variety of mission analysis and operations programs (see Section 5.0) to improve the modeling of aerodynamic forces and torques.

A.3 ORBIT-AVERAGED COEFFICIENTS DETERMINATION

For inertially stabilized spacecraft, the velocity vector slews through 360° in the body coordinate frame over the course of an orbit, with the value of C_dA changing as it moves. Because of this, it is often necessary to calculate orbit-averaged aerodynamic coefficients. An auxiliary program has been coded that calculates these by stepping through the orbit and averaging the FREEMAC coefficients obtained at each point using the interpolation subroutine mentioned above. Steps of constant true anomaly are used, concentrating the samples at perigee, where the greatest drag occurs. The orbit averaged coefficients are obtained by:

$$C = \frac{\sum_i \rho_i V_i^2 C_i}{\sum_i \rho_i V_i^2} \qquad C = C_x, C_y, C_z, M_x, M_y, M_z, C_d .$$

Calculating the coefficients in this way accounts for the greater aerodynamic effects at perigee, especially for highly eccentric orbits. Harris-Priester tables are used for the densities.

A.4 VALIDATION OF SPACECRAFT MODEL WITH GRAPHICS PACKAGE

One impediment to the use of FREEMAC in the past has been the difficultly in determining whether or not the geometric model of the spacecraft is correct, due to the somewhat non-user-friendly input format used. This problem has been alleviated somewhat by a new capability allowing the geometric model to be

APPENDIX

The FREEMAC software referenced in the paper was presented originally in Fredo [1]. Through additions and modifications due to one of the authors (Baker) and others, the capabilities and results of FREEMAC have been enhanced and made more accessible for a variety of mission analysis and operations applications. This appendix summarizes present FREEMAC capabilities, giving some details on recent program enhancements.

A.1 FREEMAC CAPABILITIES

The original FREEMAC software presented in Fredo [1] calculated the aerodynamic force and moment coefficients of a spacecraft modeled on the computer with certain basic geometrical shapes (flat plates, spheres, cylinders, etc.). These basic shapes were subdivided into smaller planar elements, which were checked using a shadow projection technique to determine whether they were exposed to the flow or shielded by other elements. The forces and torques due to each exposed element were summed to obtain those values for the whole spacecraft, and the nondimensional coefficients were calculated by dividing the forces and torques by certain dimensioned quantities, including a reference area and length. Experimentally-determined momentum accommodation coefficients from Knechtel and Pitts [5] were used in determining the force on each exposed element.

The force and moment coefficients were determined in this manner for each direction that the wind could approach the spacecraft, as represented by different wind vector directions in the body frame. The quantities calculated for each wind vector direction were:

C_x, C_y, C_z -- Aerodynamic force coefficients
M_x, M_y, M_z -- Aerodynamic moment coefficients
C_d -- Aerodynamic drag coefficient
A -- The exposed cross-sectional area of the spacecraft as viewed down the wind vector direction

The program has been modified slightly to output the last quantity, as well as to calculate weighted averages of the above coefficients and areas over all the various wind vector locations. Such an overall average area or C_d could be used, for example, in analyzing the lifetime of spacecraft in low Earth orbit if the wind could be assumed to approach the spacecraft from all directions with roughly equal probability over the course of a mission, as might be the case for an inertially-stabilized satellite changing attitudes fairly regularly.

Another potential application of FREEMAC pertains to spacecraft in higher Earth orbits. Because the FREEMAC shadowing routine is based on a shadow projection technique, the program could be modified to calculate solar radiation pressure coefficients. FREEMAC would then provide coefficients for the largest environmental torques on spacecraft in both the lowest and highest Earth orbits.

6.0 CONCLUSION

New techniques for calculating attitude-dependent aerodynamic coefficients have been described here, along with suggestions for their use in various areas of orbit and attitude analysis. These techniques have been applied to the short-term orbit prediction of the GRO and HST spacecraft in two numerical examples. The use of attitude-dependent drag coefficients resulted in improved ephemeris accuracy, particularly when these coefficients were determined at each orbit integration step. Further work is required to validate the improvements suggested by these results, and to calibrate the FREEMAC-determined coefficients, if necessary.

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5.0 OTHER POTENTIAL USES OF FREEMAC COEFFICIENTS

In addition to the improvement in the short-term predictions noted above, using FREEMAC-determined average ballistic coefficients (or C_dA values) should greatly improve lifetime studies and long-term decay studies, especially if the target attitudes are known beforehand. Orbit-averaged C_ds or ballistic coefficients for each attitude could then be determined and used in the propagator. Alternatively, the FREEMAC coefficients obtained by averaging over all wind directions (see Section 3.1) could be used to get more accurate constant C_dA values.

Orbit determination (OD) from tracking measurements could also benefit from FREEMAC-determined coefficients. If GTDS could be modified to accept a varying value for the C_dA term in the drag equation, the effect of C_dA and density variations could be decoupled somewhat, with the effect of the C_dA variation being removed, thus leading to potentially lower residuals and greater orbit determination accuracy. The sinusoidal variation in C_dA cannot be modeled accurately by the fifth order polynomial for rho1 currently used in GTDS.

GTDS should be modified to accept a Fourier series representation of the varying C_dA, or at least a general sine curve, with the independent variable being the mean or true anomaly. The coefficients for these curves could then be calculated in the same program that calculates the orbit-averaged FREEMAC coefficients (see Section A.3).

The attitude analysis field could use FREEMAC aerodynamic torque coefficients to possible an even greater extent than the orbit field could use the force coefficients. By inserting a subroutine described in the Appendix (Section A.2) into any host program, the user can obtain the FREEMAC torque coefficients for a given body frame wind direction. Used in attitude dynamics simulators, these coefficients would result in more realistic and accurate aerodynamic torques. These coefficients could be used, for example, to predict the effect of aerodynamic torques on the drift rates of spinning spacecraft spin axis attitude. Orbit-averaged torque coefficients (see Appendix A.3) could be used to size control system components, or to determine at what torque levels (and thus altitudes) the control systems will fail.

TABLE 3 -- HST ORBIT PREDICTION RESULTS

	Epoch Elements: GTDS	End-of-Span Elements: GTDS	Method #1	Method #2	Method #3
Time	910311.0415	910317.2215			
SMA	6988.7524	6989.0337	6988.9920	6989.0567	6989.0310
ECC	.00064063	.00179858	.00179714	.00179976	.00179872
INC	28.409823	28.272128	28.414024	28.413882	28.413938
LAN	348.53786	305.25818	305.40857	305.40973	305.40927
ARP	3.944306	95.843055	95.999651	95.851540	95.910008
MAN	275.07443	20.102278	20.044183	19.866536	19.937082
Argument of latitude:		115.94533	116.04383	115.71807	115.84709

Prediction Errors:	Method #1	Method #2	Method #3
Semi-major axis [km]:	-.0417	+.0230	-.0027
Eccentricity:	-.00000144	+.00000118	+.00000014
Inclination [deg]:	+.141896	+.141754	+.141810
RA ascend. node [deg]:	+.15039	+.15155	+.15109
Arg. of perigee [deg]:	+.156596	+.008485	+.066953
Mean anomaly [deg]:	-.058095	-.235742	-.165196
Arg. latitude [deg]:	+.098500	-.227260	-.098240
Along-track position error (approx.) [km]:	+12.0	-27.7	-12.0

4.3 COMMENT ON RESULTS

Because atmospheric density and the C_dA term are so difficult to distinguish between, the accuracy of the results above is highly dependent on the density over the spans in question. Fortunately, for the runs presented above, the 90-day average solar flux across the spans averaged almost exactly 225 in both cases (see Figure 1), suggesting that the actual densities in these runs may have been close to the table values. This in turn suggests that the improvements in ephemeris accuracy noted above are real, rather than just happy coincidence.

Further experimentation with the FREEMAC coefficients is needed in any case to validate the improvement in ephemeris accuracy. Possibly a large number of runs could be made to statistically reduce the effect of the density variation.

#1 -- Average C_dA value used operationally: $C_d = 2.47$, Area = 74 m^2. Corresponds to $C_dA = 182.78\ m^2$.

#2 -- FREEMAC C_dA averaged over all body frame velocity directions: $C_d = 1.873$, Area = 78.3 m^2. $C_dA = 146.7\ m^2$.

#3 -- Best FREEMAC C_dA estimate. Using the facts that HST points its solar arrays at the sun and that the sun vector lies in the orbit plane at this time, the average C_dA in method #2 was adjusted upward to account for the greater area swept out by the solar arrays in this geometry as compared to the average over all body frame velocity directions. This readjustment was given by:

$$A_3 = A_2 + A_{s/a} * (2/\pi - 1/2)$$

where $2/\pi$ and 1/2 are the proportions of the solar array seen on average in an orbit with the orbit normal parallel to the solar array, and on average from all directions, respectively. The resulting calculation gives: Area = 86 m^2. Using a similar C_d of 1.873 gives $C_dA = 161\ m^2$. These numbers represent then the best guess C_dA for the given orbit/attitude geometry and the FREEMAC coefficients.

Again, actual tracking data was used in GTDS to obtain the initial elements and the end-of-span elements to which the predicted end-of-span elements were compared. The Harris-Priester density table for a flux level of 225 was again used in the predictions, this level being the one closest to the 90-day average flux of 224 at the beginning of the span (see Figure 1).

Table 3 shows the predicted end-of-span Keplerian elements for the three predictions and the GTDS solution, as well giving the prediction errors for the three cases. The prediction errors indicate that the FREEMAC best-estimate of the average C_dA (Case #3) predicted the semi-major axis surprisingly well (to within about 3m, as compared to about 40m with the standard numbers of Case #1). This makes the lack of improvement in the along-track position somewhat perplexing, since one might suppose the two quantities would be correlated somewhat.

TABLE 2 -- GRO ORBIT PREDICTION RESULTS

	Epoch Elements: GTDS	End-of-Span Elements: GTDS	Method #1	Method #2	Method #3
Time	910418.00	910515.21	910515.21	910515.21	910515.21
SMA	6831.8933	6827.6276	6826.7265	6827.2884	6827.6931
ECC	.00202200	.00169399	.00164543	.00169023	.00170903
INC	28.438234	28.298850	28.427451	28.427224	28.427381
LAN	153.22101	319.90855	320.20086	320.24621	320.26151
ARP	84.043841	51.170140	52.747475	50.810026	50.458236
MAN	40.158192	32.337343	43.780799	34.814229	31.085599
Argument of latitude:		83.507483	96.528274	85.624255	81.543835

Prediction Errors:	Method #1	Method #2	Method #3
Semi-major axis [km]:	-.9011	-.3392	+.0655
Eccentricity:	-.00004856	-.00000376	+.00001504
Inclination [deg]:	+.128601	+.128374	+.128531
RA ascend. node [deg]:	+.29231	+.33766	+.35296
Arg. of perigee [deg]:	+1.577335	-.360114	-.711904
Mean anomaly [deg]:	+11.443456	+2.476886	-1.251744
Arg. latitude [deg]:	+13.020791	+2.116772	-1.963648
Along-track position error (approx.) [km]:	+1551.5	+252.2	-234.0

The most notable result is the accuracy to which Method #3 predicted the semi-major axis (to within 70 m over the 4 weeks, as compared to an error of over 700 m for Method #1). The improvement in along-track error is also impressive: Methods #1 & #2 gave errors of only about 250 km, as opposed to 1500 km for Method #1.

4.2 NUMERICAL EXAMPLE: HST DATA

Tracking data for the HST spacecraft were obtained for an approximately one week period spanning 910311.0415 to 910317.2215. Since the spacecraft changed its attitude 36 times during this span, using the orbit-averaged C_d method and the force-coefficient-every-integration-step method was deemed impractical with the software currently available. Instead, the following constant C_dA cases were used for the predictions:

Note in Table 1 that the solar array angles changed with each attitude. Since each FREEMAC coefficient file is only valid for a single geometric configuration, some approximation was required here. For three of the attitudes, a file created with a 0° array angle was used, while one for 45° was used for the other four.

Atmospheric density is modeled in EPHGEN using Harris-Priester tables corresponding to flux levels at increments of 25. The table for a flux level of 225 was used in the predictions, this level being the one closest to the 90-day average flux of 236 at the beginning of the four weeks (see Figure 1).

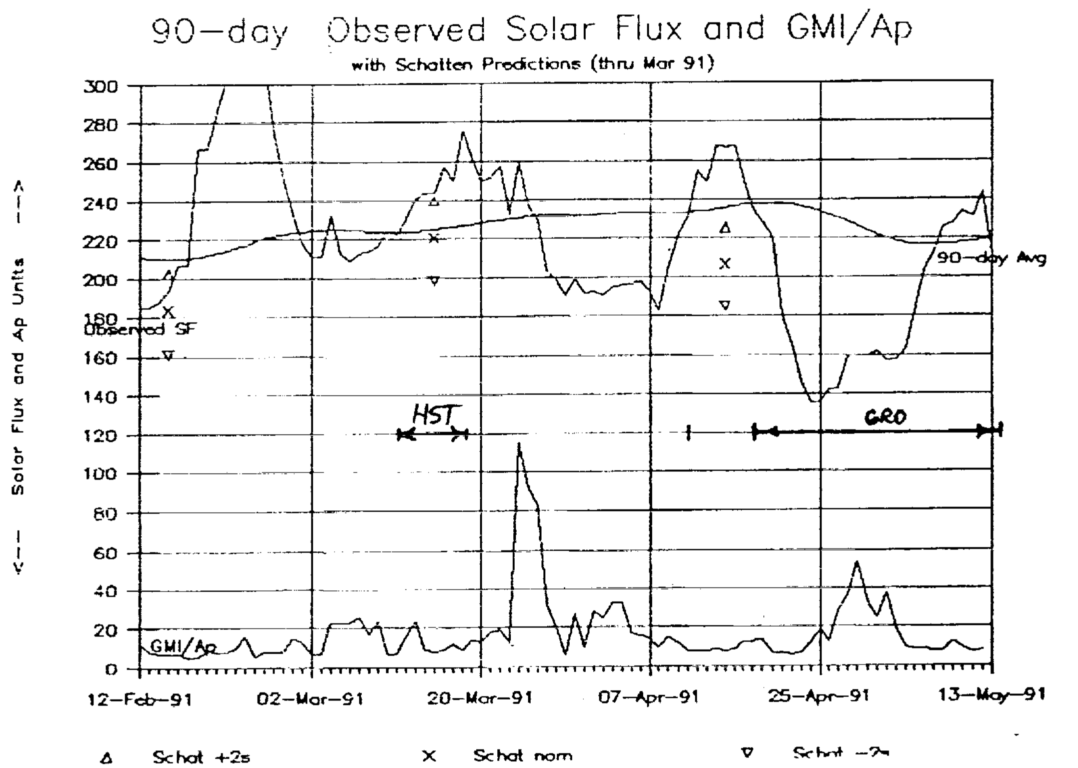

Figure 1.

Table 2 shows the predicted end-of-span Keplerian elements for these three methods, as well as the GTDS solution. The table shows the prediction errors for the three methods, as well; the semi-major axis errors and along-track position errors indicate that Methods #2 and #3 both predicted the spacecraft position more accurately than Method #1.

4.1 NUMERICAL EXAMPLE: GRO DATA

Tracking data for the GRO spacecraft were obtained for an approximately four week period spanning 910418.00 to 910515.21. The spacecraft assumed seven different inertial attitudes during this period, as given in Table 1. Predictions were made for the 4 week span using the current operational approach and the latter two methods above, based on epoch elements obtained from a GTDS solution using the real tracking data. The three predictions at the end time were then compared to another GTDS solution at the end of the span which again used the real tracking data.

TABLE 1 -- GRO ATTITUDES

Times	1-2-3 Euler Angles [deg]			Solar array angles [deg]	Average C_dA [m2]
414.05-419.03	-96.86	-18.00	-10.24	2.	93.9
419.03-428.15	-67.88	3.01	-0.51	37.	82.5
428.15-501.17	-74.76	0.22	-49.90	48.	80.2
501.17-504.16	-74.76	0.22	40.20	52.	96.8
504.16-507.16	-67.86	6.00	-0.90	51.	94.8
507.16-510.17	-10.98	-31.04	64.20	.6	91.5
510.17-515.22	-144.93	-30.05	-81.55	-11.	92.7

The three prediction methods were:

#1 -- Current operational approach: a C_d of 2.2 and an average area of 47 m^2 were used for the whole 4 week period. (Note that this area is actually the FREEMAC area averaged over all body frame velocity vector directions.)

#2 -- Average C_dAs used for each attitude. Orbit-averaged C_dA values were calculated from the FREEMAC coefficients for each of the seven attitudes and were applied as constants over the respective time spans. Mid-span orbital elements were used in the orbital averaging, with the ascending node drift rate approximated beforehand.

#3 -- Force coefficient vector $[Cx, Cy, Cz]^T$ extracted and applied at each integration time step.

a week or so (for periods in which the orbit orientation does not change too much). Section A.3 of the Appendix describes a subroutine that has been developed to calculate these orbit-averaged coefficients.

3.2 CONSTANT COEFFICIENTS FOR EACH INERTIAL ATTITUDE

The next level of complexity is to calculate drag using C_ds held constant over various spans of the prediction period. This segmentation technique can be used for inertially-stabilized spacecraft that change viewing attitudes regularly, for example. It has the advantage of being applicable to current software, with the constant C_dAs being precalculated from the FREEMAC results. This method does lose some accuracy, however, if the orientation of the orbit plane changes significantly over the prediction span.

3.3 COEFFICIENTS DETERMINED EACH INTEGRATION STEP

The third and most accurate approach is also the most rigorous computationally: as with other perturbing forces (third body, Earth asphericity, etc.) a FREEMAC-determined drag force is calculated at each orbit integration step. The complete aerodynamic force coefficient vector $[Cx, Cy, Cz]^T$ is interpolated from the FREEMAC coefficient file at each time step; this allows for the determination of the aerodynamic effect on not only the in-plane elements, but on inclination and node as well.

The third approach above was implemented on EPHGEN, a PC-based orbit generator using the GTDS 12th order Cowell integrator. Test runs have shown that this approach increases run time by approximately 45%, an increase which, though it seems large, is roughly equivalent to increasing the order of the Earth gravitational potential model from 16x16 to 21x21.

4.0 NUMERICAL EXAMPLES

To assess the accuracy benefits to be gained by using the above FREEMAC-based approaches, two numerical prediction cases were run and are presented below, the first using GRO data, the second using HST data. For all the predictions, the 12th order Cowell integrator in EPHGEN was used with a 60 second step size. Both solar and lunar gravitation perturbations were applied, and a 16x16 geopotential model was used with a cosine power of 2 and a bulge angle of 30°. The mass of GRO was taken as 15700 kg, and that of HST as 11328 kg.

make the use of more accurate attitude-dependent aerodynamic coefficients easy to implement in a variety of applications. These routines, based on the FREEMAC program described in Fredo [1], are described in some detail in the Appendix and are summarized below.

FREEMAC calculates the spacecraft aerodynamic force, moment, and drag coefficients as a function of body frame velocity direction using a user-input geometrical model of the spacecraft, a shadowing technique, and free molecular flow theory. The coefficients are written to a file for velocity vectors spaced every 10° in azimuth and elevation in the body frame. A subroutine has been written that interpolates quadratically between these values to obtain accurate coefficients for any given input body frame velocity vector. Because this interpolation can be performed quickly on a digital computer, this subroutine can be used to return aerodynamic coefficients at the same frequency that other environmental perturbations (e.g., third body accelerations, gravity gradient torques, etc.) are calculated in orbit and attitude integrators.

3.1 CONSTANT COEFFICIENTS: OVERALL & ORBIT-AVERAGED

FREEMAC-determined drag coefficients (or, alternatively, C_dA values) can be applied to the orbit prediction problem at several levels of complexity and computational effort. First, constant attitude-independent C_dA values can be used for lifetime predictions and other situations where the velocity vector is known to take on essentially a random directional distribution in the body frame during the prediction period, as is the case, for example, for an inertially-stabilized spacecraft changing its attitude frequently. In these situations, a FREEMAC-calculated C_dA values averaged over all possible body frame velocity directions could be applied. These average C_dAs can be used in all the current software. They have the advantage of being detailed calculations based on a model of the spacecraft, rather than being just the "eyeball" estimates of the spacecraft area currently used times a drag coefficient value of 2.2.

For spacecraft stabilized in a constant orbit-based reference frame in which the velocity vector remains fixed in the body frame, a FREEMAC-determined C_dA can be interpolated from the coefficient file and can be used for the remainder of the mission, without further recourse to FREEMAC. For inertially stabilized spacecraft, however, the velocity vector rotates 360° in the body frame, causing the C_dA to change sinusoidally around the orbit. The effect of this varying C_dA on orbit decay can be approximated by an orbit-averaged C_dA for time spans of less than

Telescope (HST) and the Gamma Ray Observatory (GRO). Finally, suggestions are made for other uses of FREEMAC-determined attitude-dependent aerodynamic coefficients in the orbit and attitude analysis fields.

2.0 CURRENT ORBIT DETERMINATION AND PREDICTION TECHNIQUES

Orbit determination and short-term prediction for Earth-orbiting satellites are currently performed in NASA/Goddard's Flight Dynamics Division (FDD) with the Goddard Trajectory Determination System (GTDS). GTDS uses the following equation for drag when in orbit prediction mode:

$$D = \frac{1}{2}\rho_0 \,(1+\rho_1)\, |V_r|\, C_d A\, V_r$$

where

ρ_0 = atmospheric density taken from Harris-Priester table
ρ_1 = corrective density term
V_r = relative velocity of spacecraft and atmosphere
C_d = coefficient of drag
A = satellite cross-sectional area

Parameter ρ_1 in this equation is generally solved for in the orbit determination process, then used subsequently in the prediction; it accounts for differences between the actual density and the assumed atmospheric density.

Because any C_dA mismodeling is compensated for in ρ_1, there is a tendency not to calculate the most accurate C_dA for use in GTDS, since any errors in C_dA will be removed in solving for ρ_1. Moreover, lumping the C_dA and density errors together into the term hides the fact that the C_dA product can be fairly accurately calculated if the effort is expended to do so, while the density calculation will have substantial errors in any case due to the random nature of the solar flux, which drives atmospheric density.

In practice, the drag coefficient is usually taken as 2.2 or 2.0, while the cross-sectional area is approximated from the views on the blueprint.

3.0 ATTITUDE-DEPENDENT AERODYNAMIC COEFFICIENTS

Constant C_dA values have been used in the past probably because the complexity of calculating a changing values for different mission geometries was deemed not worth the effort. In recent years, however, software tools have been developed that